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Specific discharge variability in a boreal landscape

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1. Introduction

[2] Recently, the call for new constructs of how to treat the inherent heterogeneity found in hydrologic systems has been put forward. This focuses on moving beyond the status quo of having to explicitly characterize or prescribe landscape heterogeneity in our modeling representations of hydrologic systems and suggests an attempt to explore the sets of organizing principles that might underlie the heterogeneity and complexity [*McDonnell et al.*, 2007]. This likely requires looking into the landscape and discerning the distributed response of hydrologic systems. The idea of looking into the landscape at distributed responses is not entirely new to research hydrology. The call for distributed observations has gone up time [*Klemeš*, 1986] and again [*Hornberger and Boyer*, 1995] to aid in understanding hydrological processes. The main shift to come about from taking a new vantage point of heterogeneity is to ask whether there is a simple explanation for the existence of landscape heterogeneities and process complexity, and if there are simple ways to describe organizing principles that govern their emergence, maintenance and interconnections [*McDonnell et al.*, 2007].

[3] Focusing on and increasing understanding of the emergence of heterogeneity in hydrologic response across a landscape is not a hydrological exercise for its own sake.

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Heterogeneity and/or landscape variability in hydrologic response has influence across disciplines. For example, water and biogeochemical (e.g., carbon and nitrogen) cycles operate and interact with each other at different spatiotemporal scales and, while much research has focused on understanding their cycling at one scale or another, knowledge gaps still exist in linking these cycles across scales relevant to ecosystem functioning and human interactions [*Hyvönen et al.*, 2007; *Lohse et al.*, 2009]. This goes hand-in-hand with the need for hydrologists to develop a new understanding of how all the associated components in the landscape (climate, soils, vegetation, and topography) have coevolved in the past and how they might do so in the future [*Wagener et al.*, 2010].

[4] Taking a more pragmatic view along these lines of landscape heterogeneity in hydrologic response, particularly with respect to chemical transport, a description of landscape-scale patterns in chemical outputs requires that the spatial variation of the discharge has the same resolution of sampling as sites for water chemistry [*Grayson et al.*, 1997; *Salvia et al.*, 1999; *Temnerud et al.*, 2007]. Considering total organic carbon (TOC), for example, the two main factors that determine its terrestrial export and thus its concentration in surface waters are the terrestrial sources of TOC and the hydrological mobilization of these sources [*Ågren et al.*, 2007; *Lyon et al.*, 2011]. Further, since the amount of water flowing in a stream network is spatially correlated along the stream network, the flux of chemicals from a landscape depends largely on the patterns of landscape elements together with patterns of specific discharge of water [*Temnerud et al.*, 2007].

[5] The spatiotemporal variability of specific discharge within and across catchments, however, is poorly understood and often assumed to be constant (although this is rarely verified). Such an assumption can lead to large misrepresentations in the quantification of hydrologically driven chemical or nutrient fluxes as illustrated by *Lindgren et al.* [2007]. Over the past two decades, research into variability of specific discharge (e.g., from *Woods et al.* [1995] through *Asano and Uchida* [2010]) has often considered representative elementary area (REA) concepts that hypothesize self-similarity in basin response above a threshold area and a tendency of larger basins to average the variability in local runoff patterns seen across smaller areas [*Wood et al.*, 1988].

[6] Seminal work by *Woods et al.* [1995] showed, based on field measurements, that specific discharge tended to decrease with increasing catchment area more quickly than might be expected if the catchments were random samples. Following from this benchmarking support of the concepts of REA, field studies based around continuous-flow data [*Shaman et al.*, 2004; *Uchida et al.*, 2005], low-flow chemistry [*Wolock et al.*, 1997; *Temnerud et al.*, 2007; *Didszun and Uhlenbrook*, 2008; *Asano and Uchida*, 2010], stormflow tracers [*Didszun and Uhlenbrook*, 2008], and mean residence times [*Hrachowitz et al.*, 2010] have also highlighted the decrease in hydrologic variability [i.e., *Uchida et al.*, 2005] with increasing catchment areas. However, there is still much to be learned process-wise [e.g., *Buttle and Eimers*, 2009] looking at the variability in catchments and headwater systems smaller than the thresholds often indicated in REA-type studies and the impact of such variability (both spatially and temporally) on the biogeochemical export from the landscape. These headwaters are also of interest in their own right as they represent the vast majority of stream length and are the scale at which many management decisions are made [*Bishop et al.*, 2008]. The aggregated behavior of the larger scale may also obscure the processes in different landscape elements that could respond to drivers of environmental change in ways that are not evident from the observed behavior at the REA scale [*Temnerud et al.*, 2007; *Laudon et al.*, 2011].

[7] The main goal of this study was to characterize the spatiotemporal variability in the specific discharge within the 67 km^2 Krycklan catchment located in boreal Sweden. The analyses were carried out using unique discharge observations collected during three separate field sampling campaigns. These measurements allow for the comparison of variations in specific discharge within an autumn season between years (September 2005 versus September 2008) and within a year between the spring and autumn seasons (May 2008 versus September 2008). In addition, we explore the role of uncertainty in explaining spatial patterns of variability found in this study. This helps move beyond previous field-based studies by explicitly ruling out potential systematic error in flow measurements or area delineations as the main source of observed patterns in spatiotemporal variability. We also investigated empirical links between the observed variability and catchment properties, as well as the implications for aquatic export of chemical constituents from the landscape. Such links provide a clear framework for improving our hydrologic process understanding in this and potentially other boreal areas as it highlights how patterns of wetness (and conversely dryness) emerge across the landscape.

2. Methodology

[8] The Krycklan catchment study area has its main outlet at 64°12′N and 19°52′E in the Svartberget Long-Term Ecology Research (LTER) located approximately 50 km northwest of Umeå, Sweden. It is host to several multidisciplinary research projects related to water quality, hydrology, stream biodiversity and climate effects. Building on previous work [e.g., *Buffam et al.*, 2007; *Laudon et al.*, 2007; *Grabs et al.* 2009; *Grabs*, 2010; *Lyon et al.*, 2010], this study considers the role of the landscape in relation to the spatiotemporal variability in specific discharge seen across the main 67 km^2 boreal Krycklan catchment during three synoptic sampling campaigns.

2.1. Synoptic Sampling of Discharge

[9] Three synoptic surveys were conducted in conjunction with the present study. All surveys were conducted over 4 to 8 consecutive days during relatively stable flow. The sampling locations selected for each synoptic survey correspond to major stream confluences and ongoing field studies in the Krycklan catchment study (Figure 1). The first survey was conducted during the autumn season between 12 September 2005 and 19 September 2005 and had 78 sampling locations. The second survey was conducted during the spring season between 20 May 2008 and 24 May 2008 and had 84 sampling locations. The third survey was conducted again during the autumn between 9 September 2008 and 12 September 20 and had 72 sampling locations. From the three sampling campaigns there were a total of 55 common sampling locations where discharge was measured during each campaign. For

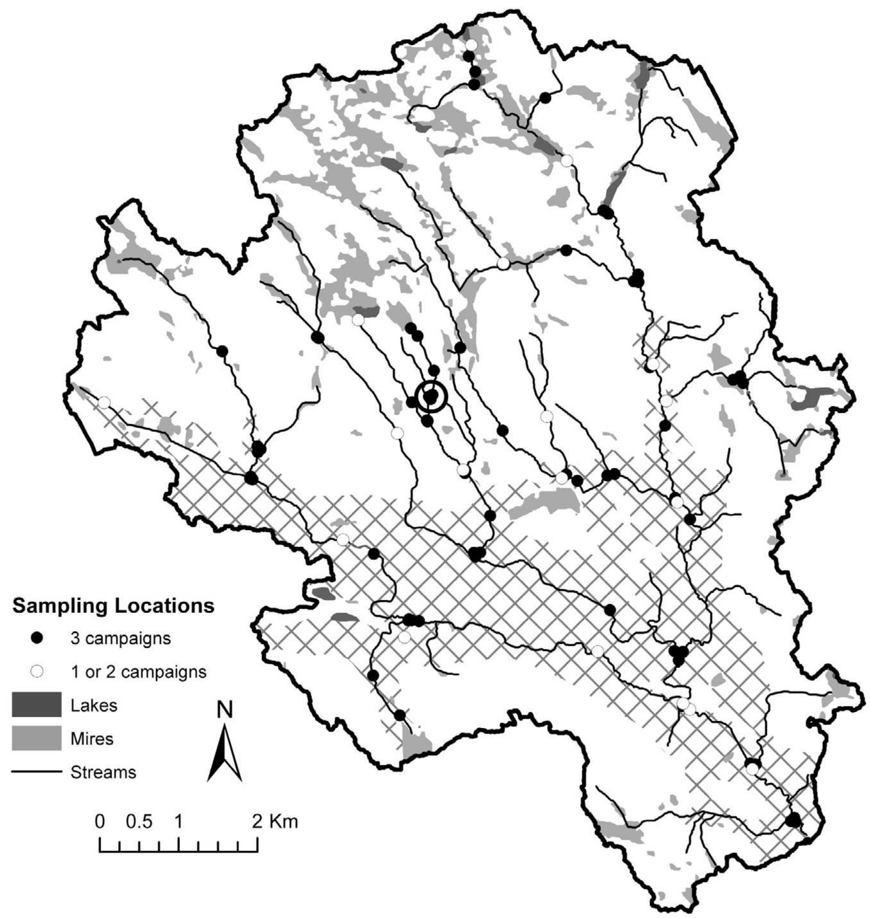


Figure 1. Map showing the location of the sampling points where flow was measured during the synoptic sampling campaigns considered in this study at the Krycklan catchment study area. As the number of measurements made in each campaign varied (due mainly to time constraints associated with the campaigns), the 55 locations that were shared by all three campaigns are indicated. The catchment outlet is located at 64°12′N and 19°52′E while the outlet of the Svartberget catchment is identified with a large circle, and cross-hatching indicates areas of deeper sediment deposits.

simplicity, the two autumn campaigns are referred to as September 2005 and September 2008, respectively, and the spring campaign is referred to as May 2008 for the remainder of this study.

[10] At each of the sampling locations, discharge was measured using either a salt dilution method or a velocity-area (current meter) method. The salt dilution method was used at the majority of sampling locations (typically more than 90% of measurements) considered as it is more appropriate for turbulent/fast flowing, small or rocky stream channels [*Day*, 1977]. This is often the case in the low-order streams at higher elevations in the Krycklan catchment. Discharge measurements were made using the salt dilution method based on a slug injection [*Hudson and Fraser*, 2005]. At sampling locations where the salt dilution method was not appropriate (typically at locations with low streamflow velocities), a velocity-area midsection method [*Maidment*, 1992] was employed to measure discharge.

[11] While the goal with each sampling campaign was to measure over periods with no rainfall, a minor rainfall event occurred during the September 2005 campaign. Measurements collected during this rainfall event were excluded from analysis. To remove potential influences of reduction of flows (recession) during the periods associated with each of the synoptic surveys and reduce the influence of the minor rain event occurring in the September 2005 campaign, discharge measured at each sampling location was scaled to one common time based on continuous measurements from a permanent discharge station where discharge is monitored continuously with a 90° V notch in a heated dam house. This station at the outlet of the 0.5 km^2 Svartberget catchment has been used in numerous studies representing both catchment-scale processes [e.g., *Bishop et al.*, 1990; *Köhler et al.*, 2008; *Haei et al.*, 2010] and conditions for all of Krycklan [e.g., *Ågren et al.*, 2007; *Björkvald et al.*, 2008; *Bergknut et al.*, 2010]. Each discharge measurement was scaled by dividing with the ratio of the discharge at the reference location when the measurement was made to the average discharge at the reference location over the entire sampling campaign. Scaled discharge measurements thus correspond to estimated average discharge at each sampling location over the entire campaign.

[12] In addition to measuring discharge at each of the sampling locations, water samples were manually grabbed from the stream to determine dissolved organic carbon (DOC) concentrations for the May 2008 and September

Table 1. Landscape Characteristics (and Relevant Metadata) Considered in the Factor Analysis and Related to the Variations in Specific Discharges From the Three Synoptic Sampling Campaigns[a]

Landscape Characteristic	Methodology (Data Source)	Resolution (Map Type)
Area	Delineated from lidar DEM similar to *Grabs et al.* [2009]	5 × 5 m (Raster)
Percent sediment	Determined from Quaternary deposits coverage map (available through Geological Survey of Sweden)	1:100 000 (Shape)
Percent wet areas	Determined from land use/land cover map (available through Lantmäteriet)	1:100 000 (Shape)
Percent till	Determined from Quaternary deposits coverage map (available through Geological Survey of Sweden)	1:100 000 (Shape)
Elevation	Calculated from lidar DEM similar to *Grabs et al.* [2009]	5 × 5 m (Raster)
Slope	Calculated from lidar DEM similar to *Seibert and McGlynn* [2007]	5 × 5 m (Raster)
Elevation above stream	Calculated from lidar DEM similar to *Seibert and McGlynn* [2007]	5 × 5 m (Raster)
Topographic wetness index (TWI)	Calculated from lidar DEM similar to *Grabs et al.* [2010]	5 × 5 m (Raster)
Shortwave radiation	see auxiliary material	5 × 5 m (Raster)
Potential annual evaporation	see auxiliary material	5 × 5 m (Raster)
Tree volume	Determined from National Forest Inventory map (Available through Department of Forest Resource Management, Swedish University of Agricultural Sciences)	5 × 5 m (Raster)

[a]For characteristics that are distributed in nature (e.g., Slope), the average across the area considered was used in the factor analysis.

2008 samplings. Samples were analyzed using a Shimadzu total organic carbon-VPCH analyzer and DOC concentrations inferred from existing empirical relationships for these sites between DOC concentrations and total organic carbon concentrations.

2.2. Estimating Specific Discharge Across the Landscape

[13] For each site in the synoptic sampling campaign, the specific discharge was determined. This specific discharge is defined as the discharge observed at a point in the stream network per unit contributing area draining to that point. The contributing area draining into each sampling location was defined using a geographical information system (GIS) topographic analysis. This consisted of delineating flow pathways and contributing areas to the stream network using a 5 m digital elevation model (DEM) derived from lidar measurements in the Hydrology Toolbox available in ArcGIS 9.2 (ESRI ®). To ensure proper delineation of contributing area extents and to make sure "digital" streams matched with the "real" streams, known streams and diversions based on site surveys and existing mapping were burned into the DEM prior to delineation of contributing areas in the GIS.

2.3. Spatial Comparison Across the Landscape

2.3.1. Landscape Characterizations

[14] There are numerous landscape characteristics that have the potential to influence how specific discharge varies across a catchment. Thus, as always, there is the question how many and which landscape characterizations to investigate. In this study, we adopted the view that there is likely to be a high amount of autocorrelation between main topographic features, soils, and land use as these characteristic (in this landscape) tend to develop in concert. As such, some subset of all potential characteristics motivated by investigations in this area [e.g., *Laudon et al.*, 2007; *Grabs et al.*, 2009; *Lyon et al.*, 2010] should suffice (Table 1). While this list of 11 parameters is by no means a comprehensive representation of possible landscape characteristics, we feel this is a fair cross section of the potential landscape characteristics often considered.

[15] Each landscape characteristic in Table 1 requires some quantitative representation for a given contributing area to compare with the specific discharges. For area, the total contributing areas were used. Slope was derived for each DEM pixel and the average occurring in the contributing area was considered. Similarly, the topographic wetness index [e.g., *Beven and Kirkby*, 1979] was computed for each DEM pixel and the average considered. The elevation and elevation above stream are average values determined from topographic analysis of the DEM [e.g., *Seibert and McGlynn*, 2007; *Grabs et al.*, 2009; *Grabs et al.*, 2010]. The percentages of land and soil coverage (i.e., tills; sediments; and wet areas as wetlands, mires, and lakes) were determined in the GIS per each contributing area based on the available local land use and soil classification maps. Readers interested in these characterizations are referred to *Laudon et al.* [2007] or *Lyon et al.* [2010] for more details.

[16] The final landscape "characteristics" considered were the average tree volume, the yearly net shortwave radiation, and the potential annual evaporation. Values of average tree volume for each contributing area were determined from forest maps for 2005 over the entire Krycklan catchment available through the Department of Forest Resource Management, Swedish University of Agricultural Sciences. These values were assumed to not change significantly between 2005 and 2008. Yearly net shortwave radiation was calculated as the sum of total monthly total shortwave radiation maps calculated in SAGA GIS 2.06 [*Conrad*, 2007; *Böhner et al.*, 2008]. Potential annual evaporation was calculated by summing monthly potential evaporation estimates using the radiation-based Turc equations [*Maidment*, 1992; *Xu and Singh*, 2000]. See auxiliary material for full details and parameter values used in calculating both the net shortwave radiation and the potential annual evaporation for the Krycklan catchment.[1] Similar to the forest volume, these values were assumed to not change significantly between 2005 and 2008 and were determined as long-term averages.

2.3.2. Relating Landscapes to Specific Discharge

[17] To test the relation between landscape characteristics and specific discharges, a multivariate common factor analysis (FA) was performed. Only the 55 common sampling

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011wr011073.

Table 2. Final Adequacy Statistics of Kaiser-Meyer-Olkin (KMO) and Bartlett's Test Scores for Factor Analysis

Statistic	All Catchments	<10 km^2	<3 km^2
KMO	0.603	0.572	0.528
Bartlett's	<0.001	<0.001	<0.001

locations were used in the FA to avoid any potential bias. FA was performed under three cases: (1) considering all catchments, (2) considering those draining areas less than 10 km^2, and (3) considering those draining areas less than 3 km^2. This was done to investigate for potential changes in interactions between landscape characteristics and specific discharges across spatial scales and, with respect to the set of smallest catchments (those draining areas less than 3 km^2) limit potential correlation errors due to using nested subcatchments.

[18] FA, also called principal axis factoring, was performed using the oblique (nonorthogonal) rotation method Oblimin (δ = 0) and Kaiser normalization (using SPSS (Statistical Package for the Social Sciences) v19). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy tests whether the partial correlations among variables are small enough to ensure the validity of the FA. In addition, a Bartlett's test of sphericity tests level of correlation between the variables considered in a FA to determine if the combination of variables are suitable for structure detection. In FA the variance of a single variable is decomposed into common variance that is shared by other variables included in the model and unique variance that is unique to a particular variable [*Gauch*, 1982]. FA can be interpreted in a similar manner to principal component analysis (PCA), with the difference that PCA considers only the total variance and makes no distinction between common and unique variance whereas FA does [*Gauch*, 1982]. Oblique rotation allows the factors in FA to correlate. If the factors are truly uncorrelated, orthogonal and oblique rotation produces similar results [*Costello and Osborne*, 2005].

[19] To apply the FA in this study, all landscape characteristics and specific discharges were tested together with poorly performing variables identified and removed in an iterative manner. As such, if a variable made the matrix indefinite (i.e., the eigenvalues were not positive) or the FA did not converge (after 100 iterations) or if KMO < 0.5 and Bartlett's test >0.01, the FA was considered not valid to perform and those variables with the lowest communalities after extraction were removed. Thus, starting with the full set of landscape characteristics considered in each FA, the variables with negative impact on the FA were identified and removed and the FA was repeated with the remaining variables. This procedure of variable removal was repeated until a valid FA was achieved (which, as such, may not contain all the variables considered in Table 1) that meets the previously stated criteria. Table 2 summarizes the final adequacy statistics achieved for the FA cases considered. It should be noted that, based on analysis of Scree plots (not shown) for each FA case considered, a minimum number of common factors equal two was appropriate (i.e., eigenvalues above 1) in all cases considered.

2.4. Assessing the Potential Influence of Errors in Flow Measurement and Catchment Delineation

[20] Errors in flow measurements and catchment area delineation are always present. These errors might have a systematic influence on the contribution to the catchment size-related pattern observed in the variability of specific discharge. For example, assuming a random error of a certain absolute size associated with catchment area calculations on flows would have a larger influence on the specific discharge in small catchments than in large catchments. This leads to the hypothesis that the observed decrease in the variability of specific discharge as catchment area increases is simply an artifact of a constant level of random error.

[21] To test this, a Monte Carlo modeling exercise was conducted to determine what level of random error needed in either flow measurements or catchment area estimates to reproduce the pattern of variability observed in specific discharge related to catchment size, i.e., the larger variability in specific discharge on smaller catchments compared to larger catchments. This modeling exercise of assigning error was conducted with the specific discharge determined for the May 2008 campaign. This sampling campaign was selected since it exhibits the largest range and most variability of specific discharge values. A Monte Carlo approach was used to create 1000 different "realizations" of the possible observations of specific discharge at all measurement locations (84 for the May 2008 sampling) assuming the same degree of random error in either flow measurements or catchment size.

[22] For the first approach to the error analysis, the mean and standard deviation of the errors were adjusted for all catchments at once to best reproduce the pattern of variation in specific discharge across all sizes of catchments at the same time (i.e., the entire Krycklan catchment study area) until the average standard deviation of specific discharge across all the model realizations matched that of the observed specific discharges. This approach to assign random errors assumes that any random error in stream measurements or catchment delineation is constant across all scales. The question addressed was, thus, whether a constant but random source of error (e.g., equipment error, or elevation model error) could lead to the variability observed in specific discharge.

[23] In a second approach to the error analysis constant random error across all scales was not assumed. Instead, the observations for the May 2008 sampling were separated into four catchment size classes (>10 km^2; 3 km^2 to 10 km^2; 1 km^2 to 3 km^2; and <1 km^2). These four catchment size classes were selected such that they each contained about the same number of catchments. A random error was then assigned to either the flow measurements or catchment area delineations (depending on the case being considered) to simulate the influence of uncertainty when determining specific discharge. To determine the random error population used in each catchment size class, the observed variability within each size class during May 2008 was used to optimize the mean and standard deviation of the error population. The structure for defining this random error was based on the standard error for each catchment size class observed in May 2008 assuming a normal distribution of error within each size class (i.e., the error is random). This standard error was then iteratively adjusted independently in each size class across all realizations until the standard deviation of specific discharge in each size class averaged across all the realizations matched that observed in each class for May 2008.

[24] This approach, in effect, is equivalent to optimizing the standard error for each size class of catchment needed to reproduce the observed variation in specific discharge values

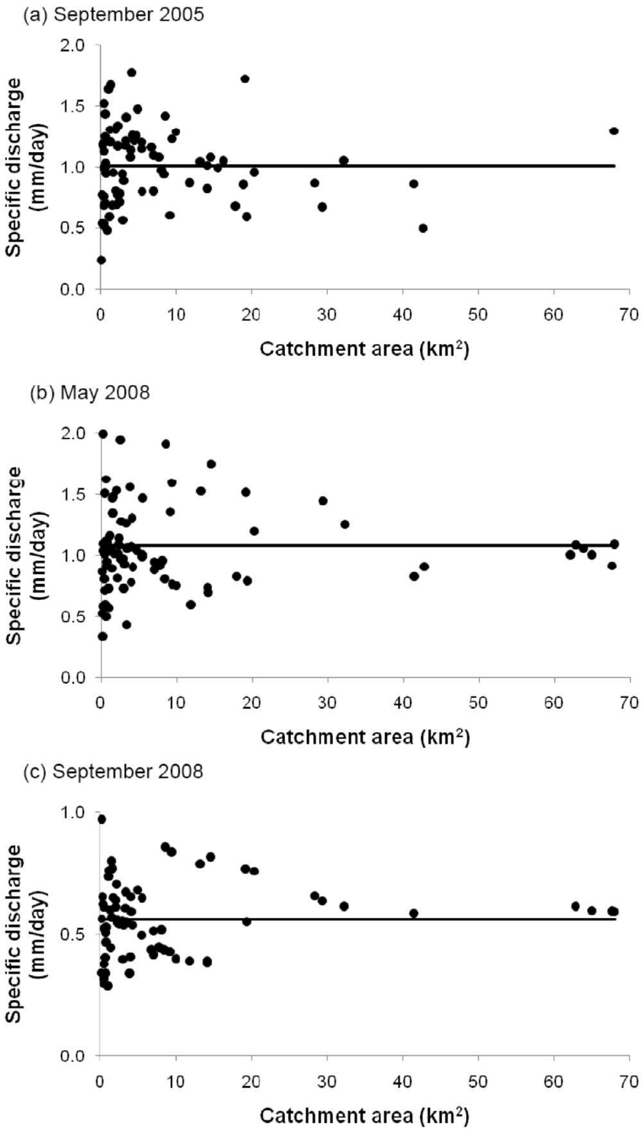


Figure 2. Specific discharge determined for the (a) September 2005, (b) May 2008, and (c) September 2008 synoptic sampling campaigns compared to contributing catchment areas. Horizontal line indicates the average specific discharge for all measurements. Please note the different scale used for Figure 2c.

for the May 2008 sampling campaign. We then used this random error structure in flow measurements and catchment size to test the hypothesis that the errors in flow or catchment delineation are responsible for the larger variability of observed specific discharge in small catchments and the lower variability further downstream.

2.5. Potential Influence of Specific Discharge Variability on DOC Export

[25] To quantify the impact of spatiotemporal variability in specific discharge on biogeochemical export, we combined the specific discharge observations with the observed DOC concentrations from the May 2008 and September 2008 sampling campaigns. The flux rate of DOC leaving each catchment sampled was determined assuming two different representations of specific discharge for this boreal landscape. The first used the observed and spatially variable specific discharge values resulting from the synoptic sampling campaigns. The second approach assumed that the specific discharge for the entire catchment could be represented using the average and spatially constant value determined from all observations during a given sampling campaign. This simple approach allowed for direct quantification of the influence of specific discharge variability within this landscape on DOC export.

3. Results

3.1. Specific Discharge

[26] There was a wide spread in specific discharge values found for relatively small catchment areas compared to those found for large catchment areas (Figure 2). The decrease in the variability of specific discharge as a function of increasing catchment area generates a characteristic "funnel" shape (narrowing of specific discharge range as drainage area increases) similar to that seen by *Woods et al.* [1995]. This funnel is centered roughly on the average specific discharge across the Krycklan catchment. This holds across the three separate sampling campaigns.

[27] The average specific discharge estimated across the Krycklan catchment was higher (roughly doubled) in May 2008 and September 2005 compared to September 2008 (Table 3), which implies relatively wetter conditions during May 2008 and September 2005 compared to September 2008. In addition, there tended to be a larger spread of specific discharge values observed in May 2008 with an interquartile range (IQR) (defined as the difference between the 75th and 25th percentiles of the specific discharge estimates) equal to 0.43 mm/d and September 2005 (IQR = 0.44 mm/d) relative to September 2008 (IQR = 0.21 mm/d). There was considerable and consistent variability in specific discharge across this landscape for all samplings (ratio between IQR and median ranging from 37% to 43%). The specific discharge could be divided into different contributing area size classes (Table 3). There was increasing variability when moving from the largest class (catchments draining more than 10 km^2) to the smallest class (catchments drain less than 1 km^2) represented by the reduction in the ratio between IQR and median values within these classes. Considering the variance of the observed specific discharges for these size classes, both the samplings from September 2005 and May 2008 exhibited the highest variance in catchments draining between 1 km^2 and 3 km^2 in area while the drier sampling from September 2008 had the highest variance among catchments draining less than 1 km^2 in area (Table 3). Comparing these size classes showing the highest variances in observed specific discharge to the next class up in spatial scale (i.e., moving from small to larger catchments), there were significant decreases ($p < 0.10$) of the variances in the observed specific discharges across all sampling campaigns.

[28] Looking across the entire study area, there was little consistency between areas that exhibited relatively higher (or lower) specific discharges under wet conditions (i.e., during May 2008 and September 2005) and those that exhibited relatively higher (or lower) specific discharges under drier conditions (i.e., September 2008) (Figure 3). There was also little connection seen between relative rankings of specific discharge comparing the two sampling campaigns carried out during wetter conditions (Figure 3c).

Table 3. Summary Statistics of Specific Discharges From the Three Synoptic Sampling Campaigns in the Krycklan Catchment Study Area[a]

Campaign	Number of Catchments	Average (mm/d)	Median (mm/d)	Standard Deviation (mm/d)	Optimized Variance $(mm/d)^2$	IQR (mm/d)	IQR/Median
				All Catchments			
September 2005	78	1.01	1.01	0.32	0.10	0.44	43%
May 2008	84	1.08	1.01	0.41	0.17	0.43	43%
September 2008	72	0.56	0.56	0.15	0.02	0.21	37%
				Catchments > 10 km²			
September 2005	18	0.94	0.91	0.28	0.08	0.22	24%
May 2008	20	1.06	1.01	0.32	0.10	0.40	40%
September 2008	17	0.61	0.61	0.14	0.02	0.10	17%
				10 km² > Catchments > 3 km²			
September 2005	24	1.15	1.17	0.25	0.06	0.20	17%
May 2008	24	1.07	0.99	0.34	0.11	0.39	39%
September 2008	23	0.55	0.53	0.14	0.02	0.20	38%
				3 km² > Catchments > 1 km²			
September 2005	17	1.01	0.94	0.35	0.13	0.59	63%
May 2008	19	1.28	1.11	0.56	0.32	0.45	40%
September 2008	18	0.61	0.60	0.11	0.01	0.16	26%
				1 km² > Catchments			
September 2005	19	0.89	0.95	0.35	0.12	0.54	57%
May 2008	24	0.95	0.95	0.39	0.15	0.45	47%
September 2008	17	0.49	0.49	0.18	0.03	0.23	48%

[a]Further, the specific discharges are divided into groupings by catchment contributing area. IQR is the interquartile range taken as the difference between the 75th and 25th percentiles of the specific discharge estimates.

3.2. Landscape Interactions and Factor Analysis

[29] FA (Figure 4a) demonstrated that during the relatively drier September 2008 sampling the specific discharge of streams in the Krycklan study catchment were positively related to both the area of wetlands and the average elevation while it was inversely related to potential annual evaporation. This is seen by the common orientation and distance from the origin of these characteristics along one of the main factor axes. The May 2008 and September 2005 specific discharges, however, were less related to these (or other) landscape characteristics.

[30] To test if relationships between landscape and specific discharge changed moving from large to small catchments (and explore statistical independence among the headwaters), FA was repeated for progressively smaller subsets of catchments defined by contributing areas less than 10 km^2 (Figure 4b) and less than 3 km^2 (Figure 4c). There was a consistent direct relationship between percentage of wet areas and average elevation and inverse relationship with potential annual evaporation for the September 2008 campaign when looking at smaller catchments. The relationship of specific discharge to these characteristics in smaller catchments were weaker in both May 2008 and September 2005, when soils were wetter and specific discharges were higher. It should be noted that under the criterion considered in this study, the percentage till characteristic was never included in any of the final FA variable sets.

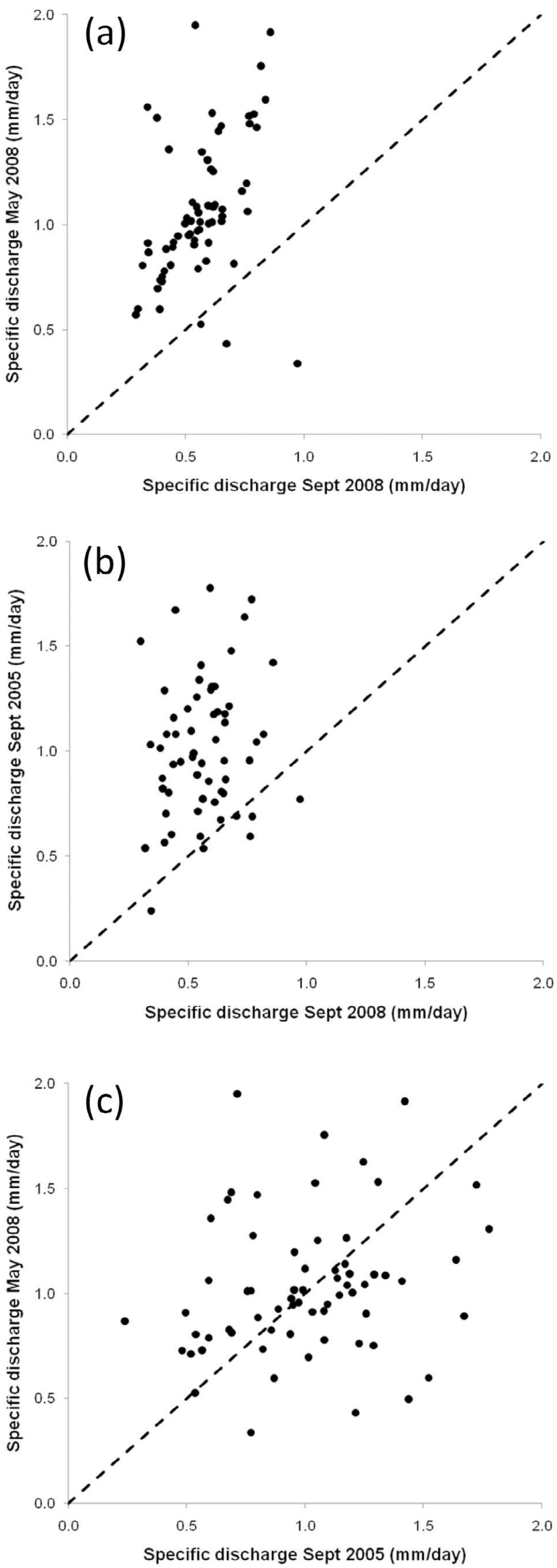
[31] The results of the FA can be further illustrated through simple regression (Figure 5). Clearly, there is a positive relationship between percentage wet areas and specific discharge and a negative relationship between potential annual evaporation and specific discharge during the relatively drier September 2008 sampling. While the general trends for such relationships remained, their strength decreases for either the May 2008 or September 2005 specific discharges (similar to what was seen in the FA).

3.3. Potential Influence of Flow Measurement and Catchment Area Calculation Errors

[32] To test whether measurement errors were responsible for larger between-catchment variation in specific discharge for smaller catchments than larger catchments, the mean and standard deviation of errors in flow measurement or catchment area delineation were determined (Table 4). The single size of error (either absolute or relative) in flow optimized to reproduce the variability for the entire catchment was 3 L s^{-1} or 2%. The error in catchment delineation was 10 ha or 1%. The single optimized error value, however, did not successfully represent the pattern of variation in specific discharge as a function of catchment size (r^2 of 0.01 to 0.02 in Table 4 and Figure 6). When considering four separate catchment size classes, the size of the random errors needed to reproduce the specific discharge variability within each size class varied across the four catchment size classes (Table 4). The absolute/relative error in flow varied from 2 L s^{-1}/41% in the smallest catchments to 80 L s^{-1}/18% in the largest size class. The absolute/relative error in delineating catchment size varied from 10 ha/19% in the smallest catchments to 230 ha/7% in the largest size class. Combining these different optimized random errors across the different size classes it was possible to better reproduce the variability in observed specific discharge for the May 2008 campaign than when using a constant error for all size classes (Figure 6).

3.4. Potential Influence of Specific Discharge Variability on DOC Export

[33] Observed DOC concentrations in the stream water sampling demonstrated less variability across the Krycklan catchment study area during the May 2008 sampling



compared to the September 2008 sampling. The median DOC concentration observed in May 2008 was 12.9 mg/L with an IQR of 3.9 mg/L giving an IQR/median ratio of 30%. Counter to this, the median DOC concentration observed in September 2008 was higher at 18.7 mg/L with an IQR of 7.0 mg/L giving an IQR/median ratio of 38%.

[34] The DOC concentrations observed throughout the stream network were used to estimate DOC fluxes. Using the spatially variable specific discharge observations allowed for representation of more variability (higher range) in the estimated DOC fluxes compared to using a catchment average spatially constant specific discharge to represent all positions in the stream for the May 2008 sampling campaign (Figure 7a). Across all sampling locations, there is an 18% reduction in the overall variability of estimated DOC export when using one constant catchment average specific discharge (IQR/median = 30%) relative to using site specific variable values (IQR/median = 48%). This corresponds to an average absolute difference in DOC export of 28% comparing flux estimated using a constant versus a variable specific discharge for the May 2008 sampling campaign.

[35] Looking at the September 2008 sampling, the variability in DOC export estimated is quite similar when using the variable specific discharges relative to the catchment average values. The IQR/median for DOC export across all sites considering variable specific discharges is 38% while it is also 38% when using a catchment average constant specific discharge (i.e., there was no change in the overall variability represented in the estimated DOC export). Regardless of this similar representation in the variability in DOC flux, there was an average absolute difference in DOC export of 20% comparing flux estimated using a constant versus a variable specific discharge for the September 2008 sampling campaign.

4. Discussion and Concluding Remarks

[36] There was great variability with regard to the specific discharges measured for the Krycklan catchment (Figure 2). This variability increased for smaller catchments and was largest for the headwaters of the system (Table 3). In particular, the smallest catchments (less than 1 km^2 for May 2008 and September 2008 and less than 3 km^2 for September 2005) exhibit the most variability (defined as IQR/Median in Table 3). The range of specific discharge observed in this current study spans about the same relative range as observed by *Woods et al.* [1995]. For catchments with larger contributing areas, there tends to be relatively less variability and the specific discharge roughly approaches the overall catchment average value (Figure 2). This creates the classic funnel shape hydrological observations moving downstream and increasing catchment areas [e.g., *Wood et al.*, 1988; *Woods et al.*, 1995; *Temnerud et al.*, 2007].

4.1. On the Potential Role of Error

[37] Introducing a uniform standard error assigned randomly in either flow measurements or catchment area

Figure 3. Specific discharge comparisons between (a) May 2008 and September 2008 (r^2 = 0.11 for a fitted linear trend), (b) September 2005 and September 2008 (r^2 = 0.02 for a fitted linear trend), and (c) May 2008 and September 2005 (r^2 = 0.05 for a fitted linear trend). The dashed line shows a 1:1 relationship.

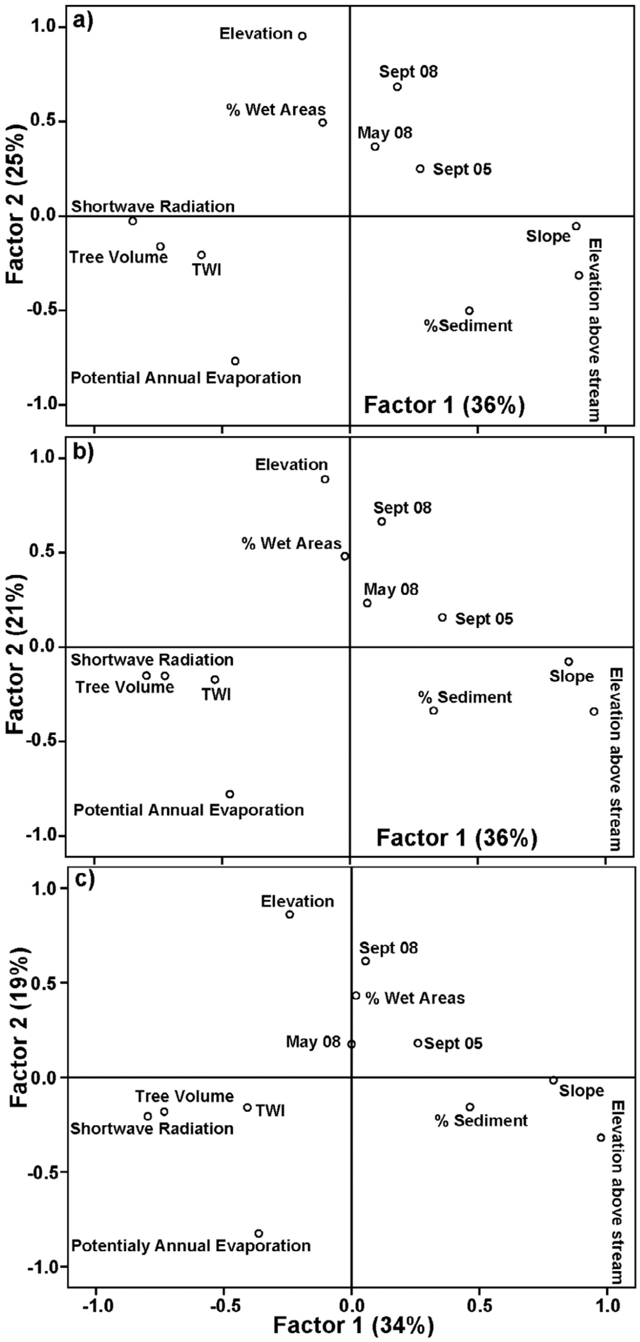


Figure 4. Factor analysis showing the multivariate relations between the landscape characteristics in Table 1 and the synoptically observed specific discharges from the three campaigns for the specific discharges across (a) all catchments, (b) those less than 10 km^2, and (c) those less than 3 km^2. The number in parentheses on each axis indicates total variance explained by each factor.

calculations across the entire range of catchment sizes could not produce results similar to those seen in this study, i.e., a decrease in specific discharge variability with increase in area. To achieve the observed results, different error distributions and thus standard errors were needed for different size classes of contributing areas (Figure 6). Dividing the catchments into four size classes and optimizing a standard error in flow or area delineation made it possible to reproduce the characteristic "funnel" shape in specific discharge variability versus area. But the errors needed in flow were not in agreement with the potential size of these errors. A 40% error in flow measurement on the small catchments, or even a roughly 30% error on the 1 km^2 to 10 km^2 catchments (Table 4) is not realistic. The errors in flow needed to give the patterns of variability in specific discharge are greater than estimated from repeated flow measurements (about 5%).

[38] The relative error representing these optimized standard errors can be put into perspective by comparison with the confidence intervals provided in the study by *Woods et al.* [1995]. From their Figure 4, for flows approximately of the same order of magnitude seen at Krycklan (about 5–500 L s^{-1}) one would roughly expect about 5% to 10% of error associated with measuring of flow. Such "real" relative error values in flow measurements are much lower than those optimized values (Table 4) needed to create the specific discharge funnel shape (Figure 6). As such, it is unlikely that the pattern seen between specific discharge and area is due to error.

[39] The plausibility of the errors in catchment delineation required to reproduce the variation in the 4 size classes (7% to 19% from Table 4) are less well documented. A 20% error in catchment area might be possible for those catchments <1 km^2 or those from 1 km^2 to 3 km^2 (Table 4). But if there were an error in catchment area, then one would expect the catchments with higher estimated specific discharges due to this error would remain consistently high across all sampling campaigns. This was not the case of the observations, since the small catchments with relatively high and low specific discharge relative to the mean varied between the three campaigns. This suggests that catchment size errors are not the source of the variability in specific discharge between the smaller catchments (e.g., Figure 3).

4.2. Temporal Variability in Specific Discharge Across the Landscape

[40] In late spring (May 2008) this boreal landscape is extremely wet due to previously near-saturated conditions during spring freshet. As the landscape transitions from spring through summer into autumn (September 2008), a drier landscape emerges (Figure 3a). This has been observed as a reduction in variability of shallow groundwater table between May 2008 and September 2008 in the Krycklan catchment study area [*Grabs*, 2010; *Lyon et al.*, 2011]. The distribution of wet areas and potential evaporation with elevation are the main landscape characteristics determining the emergence of specific discharge patterns as this boreal landscape moves from wet to dry conditions over the summer (Figures 4 and 5). This is consistent with transpiration from the forest stands in this boreal system promoting the "drying out" of the landscape through the summer period. This is counteracted by the wet areas, which tend to increase with elevation, and appear to keep parts of the landscape relatively wetter through the summer.

[41] Under rewetting conditions (e.g., September 2005), however, this is negated and the relationship between dry condition specific discharges and landscape that developed over the summer months diminishes (Figure 4). This rewetting, however, may not result in exactly the same spatial distribution of specific discharge as that observed

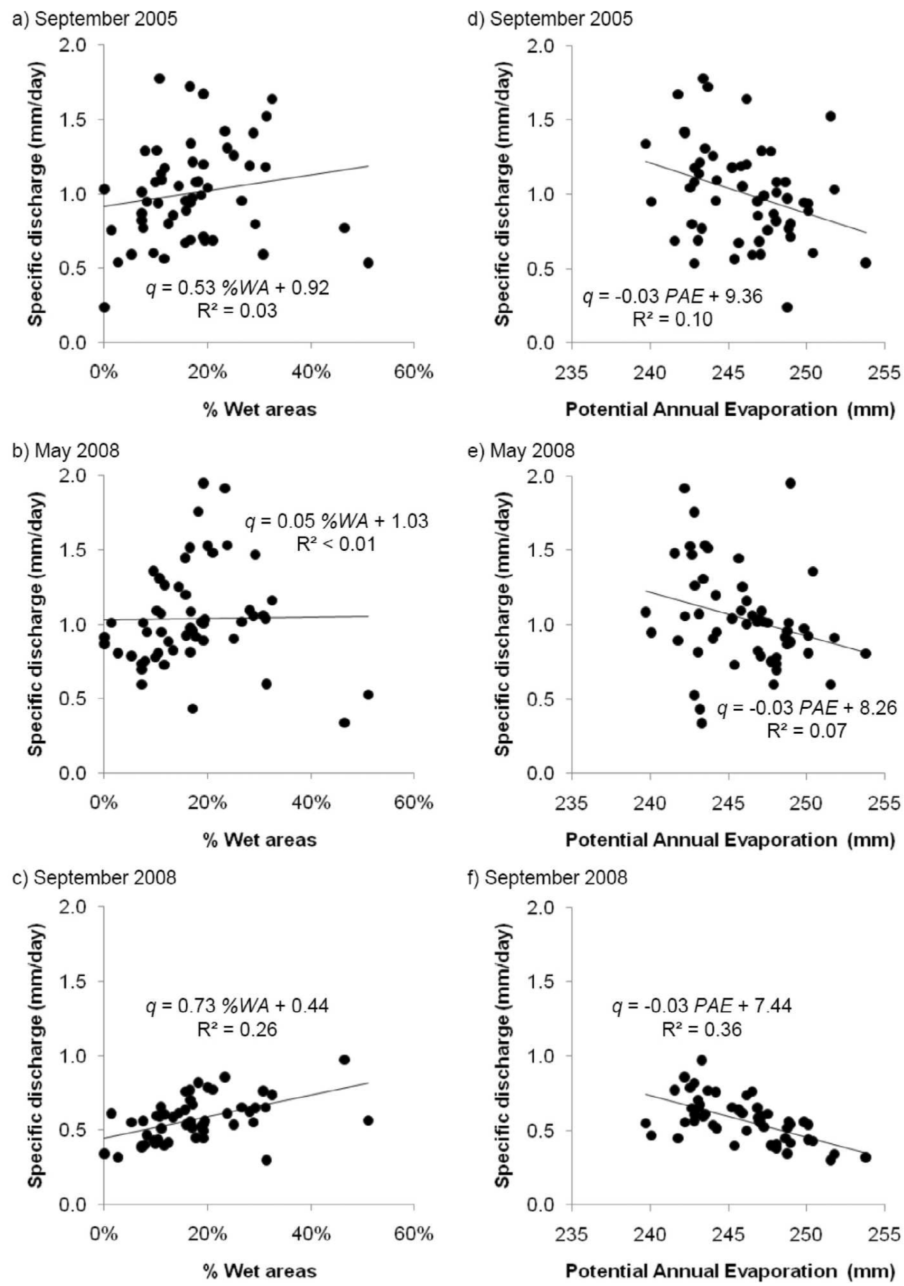


Figure 5. Relationship between specific discharge and percentage wet areas in catchments for (a) September 2005, (b) May 2008, and (c) September 2008 and between specific discharge and potential annual evaporation for (d) September 2005, (e) May 2008, and (f) September 2008.

Table 4. Standard Errors Needed to Reproduce the Specific Discharge Variability From Flow Measurements or Catchment Area Calculations Across the Entire Krycklan Catchment Study Area and the Size Classes Considered in the May 2008 Sampling Campaign[a]

Size Class	Number of Catchments	Average Flow (L/s)	Average Area (km^2)	Standard Deviation of Flow (L/s)	Standard Deviation of Area (km^2)	Standard Error Needed in Flow (L/s)	Standard Error Needed in Area (km^2)	Error of Average Flow	Error of Average Area	Flow Error Model r^2	Area Error Model r^2
All	84	126.2	9.9	210.3	17.7	3	0.1	2%	1%	0.02	0.01
>10 km^2	19	433.0	35.4	263.4	22.5	80	2.3	18%	7%	0.02	0.26
3 km^2 to 10 km^2	26	71.2	6.0	41.9	2.4	20	0.6	28%	10%	0.19	0.05
1 km^2 to 3 km^2	15	26.1	1.9	10.8	0.6	9	0.4	34%	21%	0.02	0.01
<1 km^2	24	5.6	0.5	3.0	0.2	2	0.1	41%	19%	0.02	0.03

[a]The Flow and Area error model r^2 are for the observations against the respective standard error models.

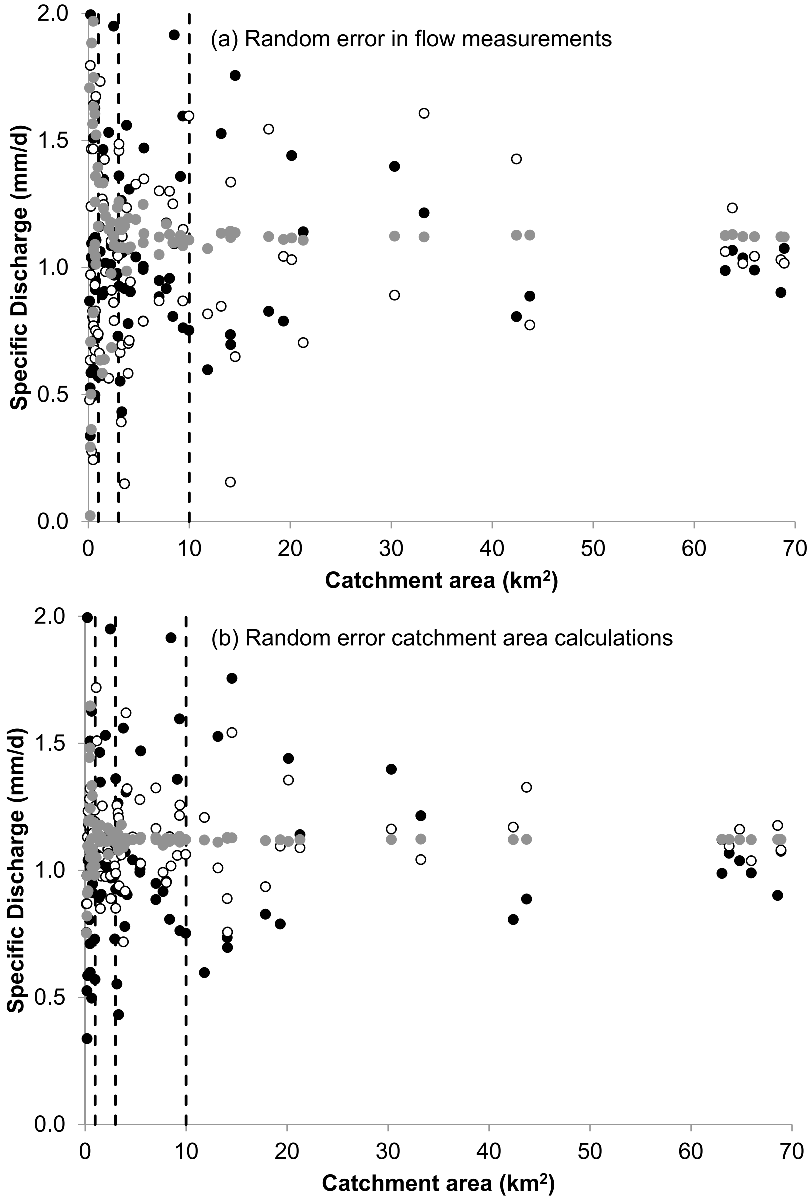


Figure 6. Error analysis model simulations (white symbols) assuming random error in (a) flow measurements or (b) catchment area calculations needed to reproduce the observed specific discharge for May 2008 (black symbols) determined in this study. The simulations here are the final averaged "realizations" that give the same pattern of specific discharge across scales observed in May 2008. Table 4 has the final optimized standard error values. The gray symbols show the pattern of specific discharge assuming a uniform random error across all scales. Horizontal dashed lines correspond to the size classes considered.

during wet conditions at the end of the spring freshet (May 2008) (Figure 3c). This is also seen by the relationship between the September 2005 synoptic campaign and the May 2008 synoptic campaign in the FA (Figure 4a).

[42] As such, the results of this study clearly indicate the ability of forests to dry out parts of the catchment over the summer months while wetlands keep wet other parts in this boreal landscape (Figure 5). Such control of the landscape forms a potential organizing principle [i.e., *McDonnell et al.*, 2007] governing (to some extent) process complexity during part of the year [e.g., *Harpold et al.*, 2010; *Jencso et al.*, 2010; *McDaniel et al.*, 2008; *Spence et al.*, 2010; *McNamara et al.*, 2005]. This raises hope for characterizing similarity and modeling hydrologic response across scales in these headwater boreal systems. But it also underlines the importance of considering the variability of specific discharge in studies of landscape export as patterns in flow may be associated with patterns in concentration that could lead to errors when estimating landscape exports with different concentrations across the landscape, but uniform specific discharge.

4.3. Implications for Transport and Biogeochemical Flux Modeling

[43] The specific discharge spatial variability found in this current study has important implications for biogeochemical transport monitoring and modeling. Consider the case of DOC export from these boreal systems. Large

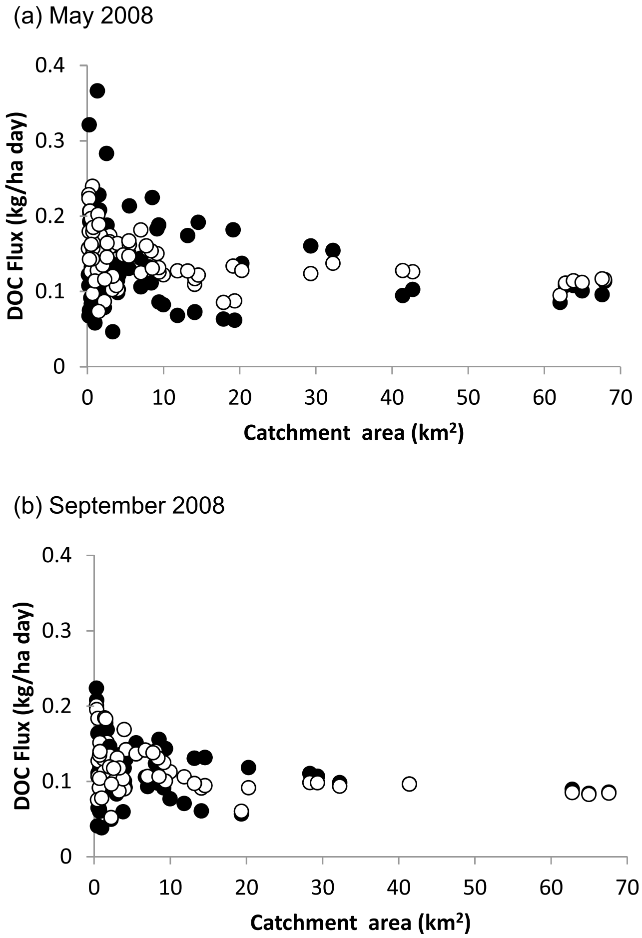


Figure 7. Dissolved organic carbon (DOC) flux estimated for the (a) May 2008 and (b) September 2008 sampling campaigns assuming either variable specific discharge (black symbols) or constant specific discharge (white symbols) across the Krycklan catchment study area.

spatial variability in DOC soil water concentrations [*Grabs*, 2010; *Lyon et al.*, 2011] and stream water concentrations [*Buffam et al.*, 2007; *Temnerud and Bishop*, 2005] have been observed across this and many other boreal systems. As such, estimating organic carbon (or other biogeochemical) exports using a uniform specific discharge will potentially lead to inaccurate export values if there is a nonrandom relation between specific discharge and concentrations at any given point in time in the catchment [*Temnerud et al.*, 2007]. This is explicitly demonstrated in this study (Figure 7) where using the uniform specific discharge lead to 20–28% average absolute error in DOC export. Further, for the samplings considered in this study, the spatial variability in specific discharge appears to have a larger influence on the variability of estimated DOC flux under wet conditions (May 2008 and Figure 7a) than relatively drier conditions (September 2008 and Figure 7b).

[44] Clearly, as demonstrated by the current study, adopting one uniform specific discharge value at the catchment scale is troublesome and would not allow for capturing the full extent of the spatial variability present in the system. This is consistent with the general interactions seen between temporally varying flow-generating zones that mobilize spatially distributed source zones [*Basu et al.*, 2010] or the specific interactions seen in Krycklan between riparian source zones and temporal water table fluctuations [*Seibert et al.*, 2009]. Still, there appears to be some connection between specific discharge and the landscape for part of the year (Figure 4). This provides some basic organizing principles around which to quantify the current state of hydrological processes in this boreal landscape. The combined roles of forests and wet areas, for example, create landscape factors that are "latent" under wet conditions (e.g., May 2008 and/or September 2005) and more "patent" in drier conditions (e.g., September 2008).

[45] The understanding of current interactions between landscape and hydrologic response in boreal systems is crucial to the development of effective and efficient future management scenarios that must both consider streamflow conditions at ungauged locations and allow for interpretation of hydrochemical behavior [*Buttle and Eimers*, 2009]. This is particularly true with regards to estimating chemical fluxes (e.g., DOC) from current and potential future boreal forested landscapes.

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